CERAMICS AT THE NATIONAL SCIENCE FOUNDATION (NSF)—TRENDS AND OPPORTUNITIES

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ABSTRACT

The field of ceramics has a long history, as well as being a very active area of research today. Broad areas of importance in ceramics research include innovations to everyday materials, endurance materials, energy efficiency, and complex integration projects. The Ceramics Program (CER) at the National Science Foundation (NSF) within the Division of Materials Research (DMR) is focused on fundamental science conducted by single investigators and small groups. Ceramics research—science, engineering, and education—is much broader than this one program; a significant amount of funding directly supporting ceramics, or with outcomes important to the ceramics community, is found elsewhere within NSF. New funding modalities (international, industrial, and group efforts, and strong linkages between theorists and experimentalists) are helping to meet today's challenges.

OVERVIEW OF THE CERAMICS PROGRAM AT NSF

The Ceramics Program (CER) within the Division of Materials Research (DMR) serves as the National Science Foundation's (NSF's) primary point for basic materials science research on ceramics (including glasses), with ~100 to 125 awards supported at any given time. Awards are typically four years in duration and the primary recipients are investigators at academic institutions. CER supports basic research and education in ceramics (oxides, carbides, nitrides, and borides) as well as diamond and inorganic carbon-based materials. The objective of the program is to increase fundamental understanding and develop predictive capabilities for relating synthesis, processing, and microstructure of these materials to their properties and ultimate performance in

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various environments and applications [1]. Topics supported include basic processes and mechanisms associated with nucleation and growth of thin films; bulk crystal growth; phase transformations and equilibria; morphology; surface modification; corrosion, interfaces and grain boundary structure; defects; and the interrelationship among experimental conditions, phenomena, and properties. The microstructures investigated range from crystalline, polycrystalline, and amorphous to composite and nanostructured. Intellectually, in addition to basic scientific research of ceramics and glasses, the program includes surface science studies and the development of characterization techniques that explore surfaces, interfaces, or the structure of ceramic materials.

It is possible to group the CER grants into several categories (Figure 1) according to traditional boundaries. The diverse character of the program comes across, and it is clear that no one topic or material dominates. Each area, and indeed each project, is both interesting and innovative. In the sections that follow, a few of today's exciting areas of ceramics research are described. The areas and the topics within them are not meant to be an exhaustive list; every research project in ceramics [2] does not fit neatly into these categories or may not fit at all.

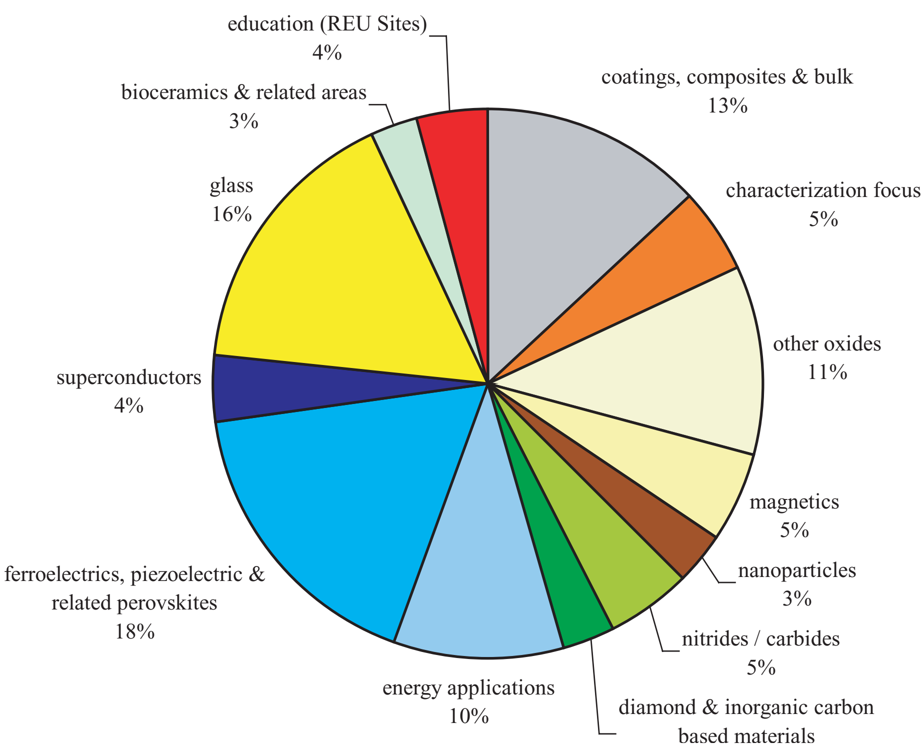

Figure 1. Distribution of CER projects.

INNOVATION IN THE STAPLES OF SOCIETY

Many Americans readily recognize both ceramics and glass and are able to distinguish between them when recycling [3]. However, the general public might be hard-pressed to convey the breadth of ceramics or glass now employed in everyday use. The 20 engineering achievements that have had the greatest impact on the quality of life in the 20th century [4] were compiled by the U.S. National Academy of Engineering. The American Ceramics Society took this list a step further and showed examples of how ceramic materials contribute to these technologies (Table 1) [5]. Additional ceramics research is required to ensure a similar impact on tomorrow's products and technology. Herein, just one example of a commonplace material, glass, is examined.

Glass, one of the oldest materials, became useful to man as far back as 5000 B.C. [6]. Glass manufacturing in the United States today employs 150,000 skilled workers and produces $22 billion worth of product annually [7]. Its uses extend well beyond just being a common material used in buildings, bottles, and automobiles; glass functions in biotechnology to help build and repair bone and tissue, in DNA sequencing, and in high-power lasers, as components in high-performance fuel cells, as optical fiber for telecommunications, and even for the long-term storage of nuclear waste [7]. Technological evolution continues in areas such as optics, photonics, nanoelectromechanical systems, solar control technology, and "smart" (reactive) glasses.

The glass industry has identified several technology challenges [8]—many concern manufacturing (production efficiency, energy efficiency and conservation, recycling, and environmental performance) [9], but one has a focus on innovative uses and enhanced functionality. Their primary goal is to create innovative products that broaden the marketplace and thereby help the glass industry remain viable and vibrant. To realize this goal, work aimed at developing new glass compositions and products through increased fundamental understanding of the relationships between glass properties, structure, composition, and surface interactions need support. Projects of interest include the development and design of "smart windows" that react to natural lighting conditions and temperatures, lighter-weight, impact-resistant containers and flat glass, fiberglass that compacts and rebounds easily, and optical fibers capable of transmitting greater amounts of information [8]. A number of technology barriers inhibit the greater utilization of glass. Some of these barriers are related to the physical, chemical, and aesthetic requirements of the finished product, whereas others concern the current limitations of existing glassmaking processes [9]. Opportunities to overcome critical challenges are characterized in five key areas: communications and electronics, structural applications, novel uses (where chemical and mechanical durability and biocompatibility are significant technological issues), surfaces and coatings, and advanced processing and control [10]. Several high-priority activities, considered critical to greater functionality, are the development of nonoxide glasses (for the communications and electronics area) and research, including theory, in surfaces (reactive, passive and modified) [9]. Two examples of NSF-funded glass research projects follow.

Table I. Ceramic materials contributions to the National Academy of Engineering's Top 20 Engineering List

Top achievements	Examples of how ceramics contribute
1. Electrification	Electrical insulators for power lines, insulators for industrial/household applications
2. Automobile	Engine sensors, catalytic converters, spark plugs, windows, engine components, electrical devices
3. Airplane	Antifogging/freezing glass windows, jet engine components
4. Safe water supply and treatment	Filters
5. Electronics	Substrates and IC packages, capacitors, piezoelectrics, insulators, magnets, superconductors
6. Radio and television	Glass tubes (CRTs), glass faceplate, phosphor coatings, electrical components
7. Agricultural mechanization	Refractory ceramic containers make melting and forming of ferrous and nonferrous metals possible.
8. Computers	Electrical components, magnetic storage, glass for computer monitors
9. Telephone	Electrical components, glass optical fibers
10. Air conditioning and refrigeration	Glass fiber insulation, ceramic magnets
11. Interstate highways	Cement for roads and bridges, glass microspheres used to produce reflective paints for signs and road lines.
12. Space exploration	Space shuttle tile, high-temperature resistant components, ceramic ablation materials, electromagnetic and transparent windows, electrical components, telescope lenses
13. Internet	Electrical components, magnetic storage, glass for computer monitor
14. Imaging: X-rays to film	Piezoceramic transducers for ultrasound diagnostics, sonar detection, ocean floor mapping and more, ceramic scintillator for X-ray computed tomography (CT scans), telescope lenses, glass monitors, phosphor coatings for radar and sonar screens
15. Household appliances	Porcelain enamel coatings for major appliances, glass fiber insulation for stoves and refrigerators, electrical ceramics, glass–ceramic stove tops, spiral resistance heaters for toasters, ovens, and ranges
16. Health technologies	Replacement joints, heart valves, bone substitutes, hearing aids, pacemakers, dental ceramics, transducers for ultrasound diagnostics, ceramic scintillator for X-ray computed tomography (CT scans) and many other applications
17. Petroleum and natural gas technologies	Ceramic catalysts, refractories and packing media for petroleum and gas refinement, cement for well drilling, drill bit coatings for well drilling
18. Laser and fiber optics	Glass optical fibers, fiber amplifiers, laser materials
19. Nuclear technologies	Fuel pellets, control rods, high-reliability seats and valves, containerization components, spent nuclear waste containment
20. High-performance materials	Ceramic materials were cited for their advanced properties such as wear, corrosion and high temperature resistance, high stiffness, light weight, high melting point, high compressive strength, hardness, and wide range of electrical, magnetic, and optical properties.

The first deals with nonoxide glasses, namely chalcogenide glasses that belong primarily to the Ge–As–Se–S–Te system with minor metallic components such as Ga, P, Sb, In, and La. This class of optical materials has received much attention because of strong scientific interest in their unique physical properties as well as their applications in the areas of photonics and telecommunications. Through studying the structure–property relationships, it will be possible to develop an atomic-scale understanding of the structural mechanisms of transport and relaxation near the glass transition temperature (Tg) in technologically relevant, complex, ternary chalcogenide glasses [10]. A primary focus addresses basic but poorly understood aspects of the intermediate-range (nm-scale) structure in these glass-forming systems and their role in controlling physical properties. Models linking these atomic structures and macroscopic physical properties such as molar volume, thermal expansivity, and optical absorption are being formulated and tested. The other key focus of this project entails studying quantitatively the effects of temperature on liquid structure and dynamics in the vicinity of Tg. The temperature-induced structural changes and the dynamics of exchange among structural species in these glasses and liquids are being characterized with different time–temperature histories by a combination of techniques. These results can be used to interpret and model the existing macroscopic thermodynamic and transport data for these glasses and liquids. Moreover, the results could have important ramifications in understanding dynamical processes in a wide variety of systems (including polymers, organic liquids, and proteins) that share a great degree of commonality in glass transition and conformational dynamics. Detailed knowledge of structure–property relationships and models of thermodynamic and transport processes of glasses and corresponding liquids are expected to have value for engineering of more efficient processes and limiting the need for extensive trial-and-error tests in complex systems. Although the studies underway are in the realm of basic science, they have long-term significance for improving the performance of key materials for a wide range of technologies including photonics, telecommunication, remote sensing, and memory devices.

A second example involves simulations that have been developed to predict and explain how materials behave under conditions that are inaccessible to experiments, for example, extreme pressures and temperatures, fragile structural states (gels), and glass—the amorphous (disordered) state of matter [11]. This research has identified new ways of making materials, improving their strength and toughness, and understanding how minerals hold up to pressure in the Earth's interior. One important finding concerns the stiffness of glass. Some glasses become softer with squeezing, a behavior opposite to that of other materials. This behavior has confounded researchers for decades. The researchers in [11] discovered the reason for this behavior, and also identified other materials that act in the same way. Namely, they showed that for all of these materials, the local arrangement of the atoms switch between two patterns of different stiffness (that have similarity to patterns found in crystalline materials; see Figure 2). This research has yielded insights into how temperature and pressure affect glass structure and properties that may provide the key to alleviating the propensity for laser-induced damage, which currently impedes the use of silicate glasses in high-power laser optics.

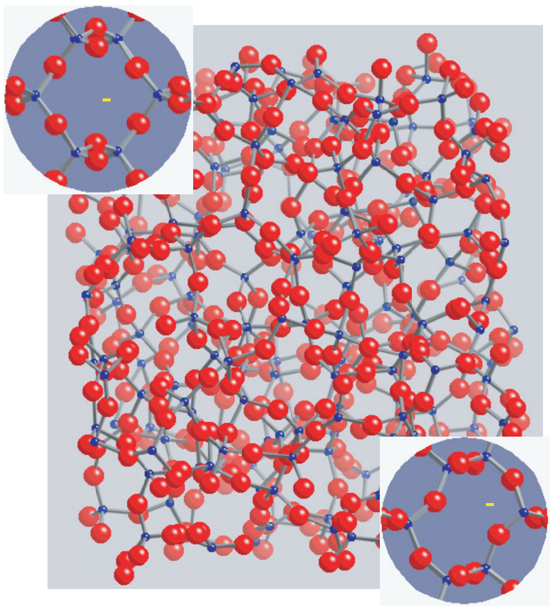

Figure 2. Simulated structure of silica glass. The elastic constant of this material decreases upon compression. In the expanded configuration, atoms tend to arrange into symmetric and, therefore, stiff (β-like) ring structures. At higher densities, these transition into partially folded (α-like) rings, which are more flexible. Image courtesy of Prof. John Kieffer at the University of Michigan, Ann Arbor.

KEY MATERIALS OF ENDURANCE

Ceramics are critical for the protection of many surfaces from (i) extreme environments such as corrosion in reactive atmospheres (e.g., monatomic oxygen and water vapour) and ultrahigh temperatures (e.g., above 2000°C) [12–13], or (ii) wear, erosion, or other damaging effects. Often, these coatings are envisaged as prime-reliant elements in design that are essential to extend performance limits, enhance reliability, and enable usage of a broader range of materials [14]. The core requirements are microstructure and chemical and physical stability during use, alongside specific mechanical properties according to the application. Coatings on tools demand increased hardness and wear longevity, whereas coatings on body implants must inhibit corrosion and be biocompatible while serving as a hermetic seal [15]. In general, carbides, borides, nitrides, and binary and various oxides (e.g., with aluminum, silicon, and zirconium) are of interest. There are four common approaches: (i) use of intrinsically suitable materials such as diamond, hydrogen-free "diamond-like carbon" (DLC), and cubic boron nitride (c-BN); (ii) thin coatings in which the property (hardness) enhancement is due to a complex, synergistic effect of ion bombardment during their deposition by plasma chemical or physical vapor deposition; (iii) use of nanostructured coatings, such as heterostructures and nanocomposites [16]; and (iv) a multilayer architecture [14].

In the first category, exploration of new materials is a key aspect. For example, a new metastable, silicon-containing phase of boron carbide (nominally B_4C) is predicted to have superior mechanical properties due to the elimination of the weak B_{12}(CCC) polytype [17]. Incorporation of Si into boron carbide could produce a material with vastly superior properties, second only to diamond as a strong, highly resilient material for wear-resistant coatings and high-energy impact applications, with potential use in blast shielding, vehicular safety, and ballistics. The first challenge, synthesis of this new material, is being approached in two ways: using radio-frequency (RF) sputtering and making use of a far-from-equilibrium or metastable plasma-melting process. The rationale is that rapid quenching of energetic vapor is needed to create conditions for deposition of metastable phases (to obtain better properties). A decrease in the B_{12}(CCC) polytype with greater Si incorporation should be accompanied by an increase in optical band gap that can be monitored by examining the absorption edge using spectroscopic ellipsometry. To quantify the average structure, radial distribution functions are being obtained from near-edge, fine-structure analysis of B, C, and Si edges (utilizing a synchrotron source).

For layered multifunctional materials (i.e., the fourth category of materials), it is important that (i) a fundamental understanding of the dynamics of structure evolution and how these influence system performance be obtained, (ii) mechanism-based models be developed, and (iii) the diversification of materials be addressed [14,18]. From a systems perspective, functionality may be viewed as depending primarily on the attributes of individuals layers, whereas the durability is usually dominated by their interplay [14]. Qualities needed are erosion and corrosion protection, enhanced durability, and thermal insulation efficiency [14]. Ideally, the majority of the incident (external) radiation should be reflected, while allowing for the transmission of any outward radiation originating at the substrate/coating interface [19]. Establishing the fundamentals governing the physicochemical phenomena within and between layers of these thermal barrier systems will enable the design of improved protection concepts for next-generation turbine systems. These systems will operate at higher temperature with substantial economic and environmental benefits derived from reduced fuel consumption and lower NO_x emissions. The information generated will also facilitate validation of system-level models used for design and durability assessments.

ATTAINMENT OF ENERGY EFFICIENCY

It is critical that we address the energy issues of efficiency, environmental impact, renewable resources, and sustainability for future generations. President Bush declared in the 2006 State of the Union Address that the United States would replace, by 2025, more than 75% of oil imports from the Middle East for added security [20]. The key factors to attaining this goal are: (i) the preservation of energy choices through the development of alternate source materials, (ii) efficient utilization of resources, (iii) scientific leadership and public appreciation of the issues, and (iv) environmental considerations [21]. Transfer over to alternate energy sources includes fundamental experiments in hydrogen-based technologies; progress in solar-energy production (which requires advances in photo-induced electron transfer processes and new materials for photovoltaic devices), coal-based energy (for which new, catalytic purification technologies are needed to reduce harmful by-products), and nuclear energy (for which disposal of spent materials is critical); innovation in biorenewables (including the proper selection of starting materials and refinement of fermentation processes); and the exploration of new chemistries. The use of high-temperature superconductors in high-efficiency power transmission cables suggests that other new-material discoveries will help achieve energy independence. For new materials, there are three key areas: synthesis, prediction of properties, and processing capabilities. Much of the optimization of resources relies on “green chemistry,” smart manufacturing, life-cycle analysis, and analytical methods. Underlying all of these priorities are implicit educational drivers, requiring a scientifically literate populace that understands the fundamental energy challenges and supports their resolution, as well as scientific experts to explore, innovate, and advise. Brief descriptions of two new CER projects dealing with energy follow.

The first one deals with photocatalysts—harnessing sunlight to enhance chemical reactions for several applications that include reducing pollution levels in air and water and providing a potential renewable hydrogen energy cycle. This research project centers on linking the subtle features of the atomic arrangements in ceramic materials with their effectiveness as photocatalysts [22]. The Aurivillius structure [23] used as the host system is characterized by $[Bi_2O_2]^{2+}$ fluorite-like layers interleaved with perovskite-like layers of the form $[A_{n-1}B_nO_{3n+1}]^{2-}$. It allows precise control of bond lengths, direct evaluation of the effects of the layered structure and ferroelectric domains on charge recombination, and provides a host for dilute doping of aliovalent cations (cations with different oxidation states than the host cation). The distinct structural characteristics of the complex Aurivillius phases provide a framework in which to improve upon the current state-of-the-art TiO_2 photocatalysts. Very little additional performance improvement is anticipated by using simple ceramics such as TiO_2, necessitating the study of complex ceramics with different structural features. Instead of searching for methods for incremental improvements, layered ceramics present the opportunity to make breakthrough advances in understanding and performance of photocatalysts. The experimental work centers on the use of diffraction, complemented with X-ray absorption and photoelectron spectroscopy to characterize the structures in detail. Density functional theory computer simulations are being performed using both energy-minimized structures and intentionally strained structures to track the electronic band structure, defect energies, and dopant clustering tendencies in parallel with experiment. By linking the simulation and experimental results, phenomenological models are being developed by the research team to predict catalytic behavior and set the foundation for future work focused on surface structures and energetics. Through the understanding of the atomic-scale workings of ceramic photocatalysts, new and improved materials can be designed. The development of photocatalysts for generating hydrogen from water could have profound political, economical, and environmental impacts. Removing CO_2 from power plant operations will reduce the total greenhouse gas emissions in the United States by ~35%, whereas hydrogen-powered vehicles will lead to an additional ~25% reduction [24].

The goal of the second research project is to develop high power output solid oxide fuel cells, essential components of a sustainable energy future. Fuel cells are clean and efficient energy conversion devices that will conserve our existing fossil fuels and can easily operate using new fuels, including hydrogen and biorenewables. The cost of solid oxide fuel cells remains high because they must operate at high temperatures. The key to lowering the temperature of operation is the incorporation of advanced cathode materials into fuel cells, which, accordingly, is the focus of this work [25]. The particular material under examination is $Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3-\delta}$ (BSCF) and the objective is combining the demonstrated excellent oxygen activity of this newly developed cathode material with the desirable electrical and mechanical properties of zirconia electrolytes. Because BSCF is chemically reactive with zirconia, it has only been possible to use this cathode with less desirable ceria electrolytes. By undertaking this fundamental study of BSCF that provides an atomistic-level understanding of the defect chemistry, structural chemistry, and oxygen ion transport properties of BSCF, it will be possible to design materials that exhibit the activity of BSCF for oxygen electroreduction, but are unreactive with zirconia. In parallel, efforts are being directed to the development of multilayer fuel cells in which the desired components (zirconia as an electrolyte and BSCF as the cathode) are separated from one another via a ceria buffer layer. Success in this arena will be an important first step toward widespread implementation of fuel cells and, ultimately, national energy security.

SOLVING THE COMPLEXITIES OF INTEGRATION

Integration of ceramics into complex and diverse systems is a key challenge for this community. Some additional examples to the ones described in the previous sections are the integration of ceramics with molecules and in nanostructures, organic–ceramic interfaces, ferroelectric random access memories (FRAM), magnetic data storage technology, nano- and microelectromechanical (NEMS/MEMS) systems, and semiconductor devices. It is essential in large interdisciplinary projects to fully understand the language and terminology used by others in the team as well as understanding the overall project goals, the range of possibilities to make advancements, and the various and sometimes conflicting constraints or demands.

The International Technology Road Map for Semiconductors (ITRS) provides a reference of requirements, potential solutions, and their timing for the semiconductor industry for a range of microelectronics: complementary metal–oxide–silicon (CMOS) devices, dynamic random access memory (DRAM), microprocessor chips, flash memories, and emerging research materials [26]. For example, continued DRAM scaling requires construction of memory capacitors in ever-smaller cell areas, while maintaining the memory capacitance to ensure reliability of stored data. This objective has resulted in the introduction of dielectric materials with a high dielectric constant (high-*k*), such as aluminum oxide, aluminates (e.g., $HfAlO_x$), and tantalum oxide as replacements for SiO_2 and silicon oxynitride [21]. Further scaling demands attention to process construction by using a thinner dielectric film and/or a higher dielectric constant material [21].

In keeping with the road map for high-*k* materials, efforts to develop suitable amorphous hafnium or zirconium dioxide layers are underway [27]. Despite their relatively low ($\leq$ 430°C) crystallization temperatures, it is necessary to keep the gate dielectric amorphous for two reasons. The first one relates to Si processing—a lower boundary on thermal budgets would affect dopant activation and could have a significant impact on overall CMOS process architecture [28]. A second reason is to maintain uniformity of coverage and properties across the entire device, and avoid grain boundaries that could enhance diffusion and introduce a serious reliability concern. The goal of this project is to systematically study the thermodynamic stability of amorphous hafnia and zirconia, and find ways to alter the crystallization temperature and energetics by doping with aliovalent metals and nitrogen. A focal point is to relate the atomic-level structure of the material to its thermodynamics, and through that knowledge elucidate practical means of controlling the amorphous phase stability.

Within the road map, the need for high-*k* materials has been delayed since fundamental performance and reliability issues, as well as issues with CMOS integration, are still under investigation [28]. The timely implementation of a high-*k* material (and metal gate electrode) will involve dealing with numerous challenging issues, including appropriate tuning of the metal gate work function, ensuring adequate channel mobility, reducing the defects in the high-*k* material to acceptable levels, and ensuring reliability [26]. Integration of this material affects critical electrical parameters (e.g., threshold and current mismatch and 1/f noise for analog devices); demands new measurement methodologies, fundamental physical data, and a suitable removal process; and is very likely to be simultaneously implemented with a new device structure [26].

CERAMICS ACROSS NSF

CER is not the only "game in town" or even the only option at NSF. CER is located within DMR, which lies in the Mathematical and Physical Science (MPS) directorate (Figure 3). MPS consists of five divisions: DMR, Physics (PHY), Chemistry (CHE), Astronomical Sciences, and Mathematical Sciences (DMS), and the Office of Multidisciplinary Activities (OMA). OMA works in partnership with these divisions across disciplinary boundaries to encourage innovative proposals that are multidisciplinary or crosscutting and could lead to new paradigms in graduate and undergraduate education or in the integration of research and education. As well, OMA provides a focal point in the directorate for partnerships (e.g., with industry, national laboratories, and other funding agencies at the federal, state, and local levels, as well as abroad). Some of the projects supported via OMA are relevant to the materials research community. Additionally, several projects supported in MPS divisions (outside of DMR) deal with specific aspects of ceramics, or could lead to valuable discoveries or developments for the ceramics community.

For example, one award in CHE (#0412198) [29] focuses on the synthesis and study of polymer precursors for ceramics. If successful, this research can be used to obtain SiC/BN ceramic mixtures, nanostructured Si-based ceramic materials with predictable and controlled microstructures, and synthetic routes to metal- or semiconductor-containing ceramic nanocomposites that may have a variety of applications, including low-*k* dielectric films and ionic electrolyte materials.

With funding from a DMS award (#0408950) [31], researchers are developing, analyzing, and implementing a novel iterative solver based on so-called hierarchical matrix techniques. Improvements in the efficiency of solving huge linear systems of equations will aid in the numerical simulation of complex physical, biological, or chemical systems, for example, in modeling the growth of ceramic nanostructures.

A site for research experiences for undergraduate (REU) at Coe College (#0354058) [32] is jointly sponsored by PHY, CHE, and the Department of Defense. Students carry out research in glass science, optics, environmental chemistry, organic synthesis, acoustics, and atmospheric chemistry, all under the common focus of spectroscopy.

Other directorates or offices at the NSF also support research or education in the area of ceramics. For example, the Office of International Science and Engineering (OISE) supports a cooperative research effort (#0322622) between investigators in the

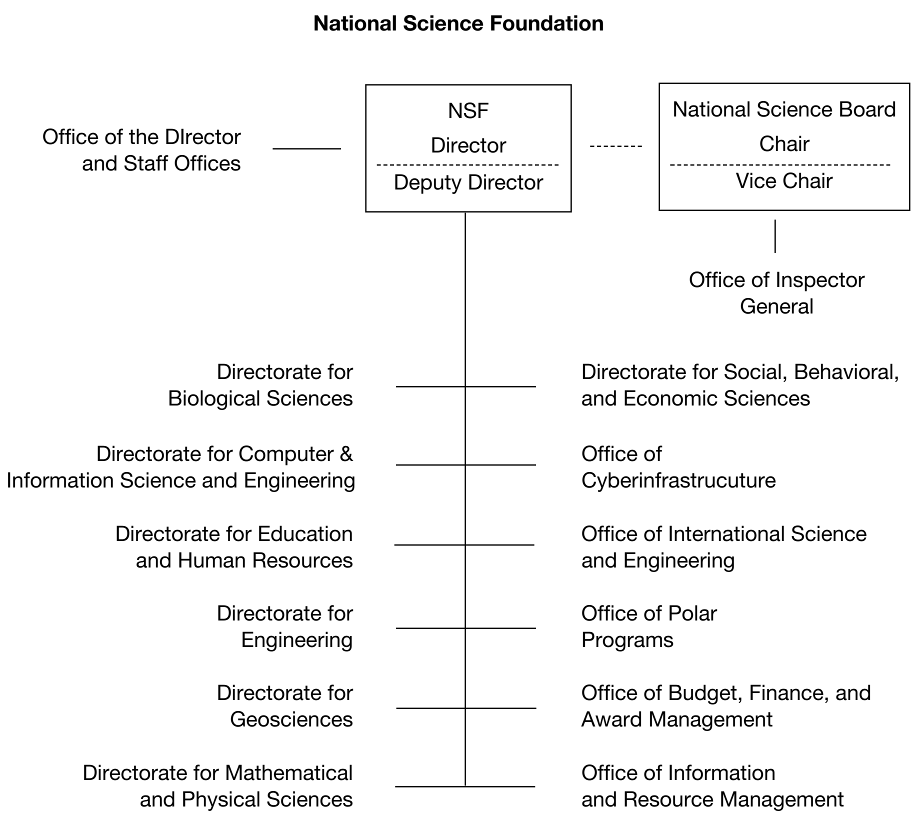

Figure 3. Organization Chart for NSF [30].

United States and Turkey [33]. They are studying the characterization and processing of ceria and alumina powders and compacts. Ceria has a critical role in chemical–mechanical polishing and it also finds application in fuel cells. Alumina, specifically polycrystalline α-Al_2O_3, is one of the most important ceramics for industrial applications due to its strength, toughness, corrosion and wear resistance, and creep properties. These properties are closely related to both microstructure and interfacial chemistry. Accordingly, analytical electron microscopy investigations, especially using energy-loss spectroscopy, are being conducted to study the microstructure and incipient formation of secondary phases.

An engineering (ENG) grant (#0457602) from the Division of Design and Manufacturing Innovation (DMI) provides funding for a new nanomanufacturing method to form nanowires and complex nanopatterns [34]. This project involves in situ transmission electron microscopy observations of the sintering (firing) of ligand-stabilized metal (Au and Ag) and ceramic (g-Fe_2O_3) nanoparticles, as well as observations of the room temperature stability of the nanoparticle arrays. If the sintering processes occurring between individual nanoparticles in these self-assembled arrays can be controlled and understood, this approach will create an ability to reproducibly manufacture such nanostructures on a larger scale by simple and inexpensive chemical methods. It holds great practical importance, especially if the promised potential benefits of nanotechnology are to be taken up by industry and exploited in the next generation of consumer electronics, chemical sensing devices, and magnetic recording media.

An interesting award (#0405383) from NSF's Geosciences (GEO) directorate investigates the structure and solubility of water and silicate in silicate melts and aqueous fluids in the Earth's deep crust and upper mantle [35]. This award states, "In addition to the application of the research to mass and energy transfer processes in the Earth and terrestrial planets, the projected experimental information also has application to the glass, ceramics, and solid and nuclear waste industries because H_2O dissolved in silicate melt and glass govern properties such as durability, density, crystallization behavior, expansivity and compressibility, element diffusion, and related transport properties. Interaction between aqueous fluids and waste-containing glass depends on the same melt and glass properties."

The Education and Human Resources (EHR) directorate supports a number of large projects (>$2.8 million each) dealing with ceramics. For example, in the Center for Advanced Materials and Smart Structures (#0205803) [36], there is keen interest in developing advanced ceramics and innovative composites for a wide variety of applications, including structural components, energy-efficient environmental and thermal barriers, and high-performance electronic and sensor materials. An integrative graduate education and research traineeship (IGERT) project, "An Entrepreneurial Ph.D. Education in Fuel Cell Manufacturing, Materials Development, and Modeling" (#0504361) [37] focuses on developing high-efficiency and environmentally friendly power generators for transportation, stationary, and portable applications. In addition to developing a solid knowledge base, doctoral students should gain skills in research, communication, teamwork, and professionalism, and innovation and entrepreneurship, enabling them to operate effectively in interdisciplinary research, development, and commercial situations.

Naturally, many of the programs within DMR (Table 2) have even stronger linkages to ceramics, particularly in terms of basic scientific research. Typically, a third of the CER projects are cofunded across programs, divisions, and/or directorates, and a few are jointly funded with other federal agencies.

ENABLING DISCOVERIES

The dominant funding mechanism within DMR continues to be single- or two-investigator grants; however, there has been a heightened interest in collaborative efforts from the research community. With NSF funding, these interactions take on several forms: (i) international collaborations, including MWN grants; (ii) interactions with industry, for example, through the GOALI announcement (98-142); and (iii) focused research groups (FRGs) with three or more investigators and centers activities, either Partnerships for Research and Education in Materials (PREM) or Materials Research Science and Engineering Centers (MRSEC). NSF's vision—to enable the nation's future through discovery, learning, and innovation—is realized by pursuing high-risk endeavors that advance the frontiers of science and engineering and produce new information and knowledge. Collaborative efforts can serve as useful modalities in this quest. International cooperation can bring together different research strengths. These collaborations may have all kinds of benefits, including cultural, but a central advantage is the stimulation of creativity that occurs with one's exposure to new experiences and ideas. Industrial cooperation with academe can certainly be a "two-way street." Benefits to universities may include extensions to in-house research capabilities, the overlay of a more practical bent; alignment of efforts with viable technology options, direct and more immediate impact on technology and its design infrastructure, and the training of students for industrial positions. Possible benefits for industry include more research-intensive activities, investigations of high-risk ideas, increased manpower for research, the training of students for future employment, and vetting of future hires. Research efforts in groups can also tackle larger, more complex, interdisciplinary problems. Sharing of equipment is beneficial, but the intellectual exchange is para-

Table 2. Programs in DMR

Topical programs (individuals and groups)	Centers and infrastructure
Ceramics (CER)	National Facilities (NAF)
Electronic Materials (EM)	Instrumentation for Materials Research (IMR)
Metals (MET)	Materials Research Science and Engineering Centers (MRSEC)
Biomaterials (BMAT)	Office of Special Programs (OSP)
Polymers (POL)	
Solid-State Chemistry (SSC)	
Condensed Matter and Materials Theory (CMMT)	
Condensed Matter Physics (CMP)	

Table 3. New awards in CER for FY06

Characteristics	Percentage
International interactions	40
Industrial ties	20
Group efforts	23
Significant theory components	17
Strong broader impacts	100

mount. Consequently, these larger efforts have a positive impact on graduate student education [38]. All FY06 awards in CER have significant broader impacts, a significant fraction has international or industrial ties, and a few involve research groups (often including a theorist) (Table 3).

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3. Recycling: for example, http://www.ehow.com/how_9162_recycle-glass.html.
4. 20th Century Engineering Achievements: http://www.greatachievements.org/.
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